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19. **Abstract**

The research conducted under this grant has been to investigate techniques for recognizing objects that are partially hidden or occluded. It was assumed that geometrical data about the objects was available either as a by-product of the CAD process used to design the object or as the output of a training phase.

There were three aspects to this work. First, recognition techniques were developed that used only a single view gray-level image. Second, complementary techniques were developed that used range images. Third, computation times for both of these techniques were studied with the intent of reducing them through the use of parallel processing.

The work on gray-level images resulted in a number of new techniques to speedup recognition. These included the concept of saliency and critical point neighborhood, and a fast matching algorithm based on k-d trees. Techniques for recognizing occluded objects that can be at varying distances from the viewer were also developed. The work with range data was aimed at the recognition and pose estimation of three-dimensional industrial parts. The major subproblems addressed were: 1) segmentation and surface parameter extraction, 2) grouping regions into a set (a Convex Region Set), and 3) Convex Region Set matching. The work to develop fast parallel versions of our recognition algorithms made extensive use of a 64 processor NCUBE hypercube multiprocessor. Speedups of 30:1 over VAX 11/780 implementations were obtained for some of the low-level image processing algorithms used in the work.

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Research into the Architecture of CAD Based Robot Vision Systems

FINAL REPORT

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February 5, 1988

U.S. ARMY RESEARCH OFFICE

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1 Problem Studied

The main theme of the research conducted under this grant has been to investigate techniques for recognizing objects that are partially hidden, or partially occluded. Two lines of work were pursued. The first works with edges extracted from a gray-level image and the second works with range data. The underlying concept in both cases is to make extensive use of a priori information about the objects that can occur in a scene. Geometrical data about the objects is assumed to be available either as a by-product of a CAD process originally used to design the object or as the output of a training phase. A more general view would characterize the database as simply a world model.

The initial phase of this work concentrated on recognizing "two-dimensional" objects at a known distance from the viewer. Two-dimensional objects have a high degree of flatness—one of their dimensions is much less than the other two. This work was then generalized to deal with objects that can be at any distance from the viewer. Initial work on true "three-dimensional" objects was also attempted.

The second line of research works with range data and sought to complement the first approach based on purely gray-level images. The eventual goal was to be able to perform three-dimensional object recognition and pose (position and orientation) estimation by using surface matching. The objects in a scene may be partially hidden by one another. The range data is obtained by laser scanner and also synthetically using GEOMOD (a solid modeling system). As with the first line of research a database of geometrical information about the objects is assumed. This takes the form of a set of solid models.

Finally, this research also addressed the issue of computation time. The role of parallel processing, in particular, that of hypercube multiprocessors, was investigated as a means to reduce the computation times for all of the recognition algorithms.

2 Summary of Results

An early result in the work on object recognition using gray-level images was to develop a technique for using the information in the database to determine which features (in our experiments features were simply distinct shaped edge segments) were the most distinguishing, given the set of objects that could occur in a scene. Distinguishing, or, as we term them, *salient*, features are determined during an off-line training phase that makes extensive use of the database. An interesting aspect of the notion of the saliency of a feature is that it is context dependent, i.e., it depends on the set of objects. A feature that is highly salient in the context of one set of objects may not be in another set. The concept of saliency allowed us to achieve improved recognition of partially hidden objects. Further details of the algorithms and experimental results can be found in the Ph.D. thesis of Jerry L. Turney entitled, *Recognition of Partially Occluded Parts* (Univ. Michigan 1986), and in the following papers: "Recognizing Partially Hidden Objects," Turney, Mudge and Volz, published in the *Proceedings of the IEEE International Conference on Robotics* (1985); "Solving the Bin of Parts Problem," Turney, Mudge and Volz, published in the *Proceedings of Vision '86*; and "Automatic Generation of Recognition Features for Computer Vision," Mudge, Turney and Volz, published in *Robotica* (1987). All of the papers have previously been transmitted to ARO (see section on publications).

The more recent work using gray-level images was built upon "critical point neighborhoods" (CPNs). These are vectors of edge points from high curvature sections of the contour of a part or object. The dimensionality of the CPN vectors is reduced using a Karhunen-Loeve transform—in our experiments 8:1 reductions were typical. The model CPNs are stored in a database organized as a k-d tree. This allows rapid matching of the model CPNs with candidates from images where recognition is being attempted. The use of k-d trees reduces recognition time from a linear search to a logarithmic one. A demonstration is presently working on 2-dimensional jigsaw puzzle parts. A large number of other experiments have been conducted including one proposed by the Airforce as a standard benchmark. It is made up of parts from a microswitch. The details of this work are described in the paper "Two-Dimensional Partially Visible Object Recognition Using Efficient Multidimensional Range Queries," Gottschalk, Turney and Mudge,

published in the *Proceedings of the IEEE International Conference on Robotics* (1987). This paper has previously been transmitted to ARO (see section on publications).

The lastest step in this work was to develop a technique for dealing with the situation where the viewer is at an unknown distance from the objects to be identified. The last phase in this work will be to deal with truly "three-dimensional" objects, i.e., objects that are not particularly flat, and may be capable of self-occlusion—the handle on a cup can be occluded by the rest of the cup from some views. Preliminary thoughts on how this last step may be accomplished are sketched in the paper, "Determining the Pose of an Object", Dolezal, Mudge, Turney and Volz (1985). This paper has been transmitted to ARO (see section on publications). This work is ongoing.

The work with range data was aimed at the recognition and pose estimation of three-dimensional industrial parts. Three major subproblems were addressed: 1) segmentation and surface parameter extraction from a range image, 2) grouping regions into a set (a Convex Region Set), and 3) Convex Region Set matching.

For segmentation, we restricted our algorithms to work with a small set of surface shapes such as planes, cylinders, and spheres, since such shapes are common in industrial parts and it is only necessary to recognize and locate a sufficient set of surface regions to uniquely distinguish the part being observed from all others that might be present. Each region was extracted using surface parameters and surface normals. Segmentation tests were performed using several noisy synthetic range images. This work was presented in the paper, "Range Image Segmentation and Surface Parameter Extraction for 3-D Object Recognition of Industrial Parts," Han, Volz and Mudge, published in *Proceedings of the IEEE International Conference on Robotics* (1987). This paper was transmitted to ARO (see section on publications).

A novel method of grouping segmented regions such that each group of regions represents a meaningful part of an object was developed. The set of regions, defined as a *Convex Region Set*(CRS), is obtained by analyzing the boundary types between pair of regions. The boundary types are classified as *convex, concave,* and *jump boundaries*. If two regions share a *convex boundary* it is assumed that they are inseparable regions, thus describing the same part (object).

The CRSs are determined by a *Region Boundary Graph*(RBG) which is defined as a graph whose nodes represent regions, and the edges represent boundaries, convex, and concave. Interestingly, the determination of boundary types does not require accurate location of the boundary, but is obtained from the region adjacent to the boundary. The technique was tested using simulated noisy range images. Results were presented in "Region Grouping from a Range Image," Han and Volz, to be published in the *Proceedings of the Conference on Computer Vision and Pattern Recognition* (1988).

A technique for matching sets of regions (CRS) was developed that used region properties and binary relationships between regions. The region property and binary relationships represent invariant properties under three-dimensional motion.

Finally, a local classification of surface types using eigenvalues of quadric coefficients was examined. Experimental results showed that the quadric invariants are poor features in practical three-dimensional object recognition.

The work to develop parallel versions of our recognition algorithms made extensive use of a 64 processor NCUBE hypercube multiprocessor. The low-level processing required in the segmentation and surface parameter extraction was successfully ported to the hypercube. A speedup of about 30:1 over a VAX11/780 implementation was achieved. This work is reported on in further detail in "Vision Algorithms for Hypercube Machines," Mudge and Abdel-Rahman, published in the *Journal of Parallel and Distributed Computing* (1987), and "An Analysis of Hypercube Architectures for Image Pattern Recognition Algorithms," Mudge, published in the *Proceedings of the SPIE Conference* (1987). Both papers have been transmitted to ARO (see section on Publications). Ongoing work is examing the port of other parts of the recognition algorithms.

Publications

1. "An Analysis of Hypercube Architectures for Image Pattern Recognition Algorithms," (T.N. Mudge), *Proceedings of the Society of Photo-optical Instrumentation Engineers Opto-electronics and Laser Applications in Science and Engineering, Image Pattern Recognition Algorithm Implementations, Techniques, and Technology: Critical Review of Technology,*

SPIE vol. 755, Los Angeles, CA, January 1987, pp. 71–83.

2. "Two-Dimensional Partially Visible Object Recognition Using Efficient Multidimensional Range Queries," (P.G. Gottschalk, J.L. Turney, and T.N. Mudge), *Proceedings of the 1987 International Conference on Robotics and Automation,* April 1987, pp. 380–386.

3. "Range Image Segmentation and Surface Parameter Extraction for 3-D Object Recognition of Industrial Parts," (J.H. Han, R.A. Volz, and T.N. Mudge), *Proceedings of the 1987 International Conference on Robotics and Automation,* April 1987, pp. 1582–1589.

4. "Automatic Generation of Salient Features for the Recognition of Partially Occluded Parts," (T.N. Mudge, J.L. Turney, and R.A. Volz), *Robotica,* vol. 5, 1987, pp. 117–127.

5. "Vision Algorithms for Hypercube Machines," (T.N. Mudge and T.S. Abdel-Rahman), *Journal of Parallel and Distributed Computing*, 4, 1987, 79–94.

6. "Solving the Bin of Parts Problem", (J.L. Turney, T.N. Mudge and R.A. Volz), *Proceedings of Vision '86,* (a Machine Vision Association of th SME Conference and Exposition), Detroit, MI, June 1986, pp. 4–21 thru 4–38.

7. "Determining the Pose of an Object," (R.M. Dolezal, T.N. Mudge, J.L. Turney, and R.A. Volz), *Proceedings of the Society of Photo-optical Instrumentation Engineers 2-nd International Symposium on Computer vision for Robotics,* SPIE vol. 595, Cannes, France, December 1985, pp. 68–71.

8. "Recognizing Partially Hidden Objects," (J.L. Turney, T.N. Mudge and R.A. Volz), *Proceedings of the IEEE International Conference on Robotics and Automation*, March 1985, pp. 72–54.

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